FEASIBILITY STUDY OF OIL SLICK DETECTION UNDER SEA-ICE

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FEASIBILITY STUDY OF OIL SLICK DETECTION UNDER SEA-ICE

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17. Abstract

This report summarizes a feasibility study on the detection of oil slick under sea-ice. In this study, the reflections of VHF signals from an oil layer under sea-ice have been estimated and verified by laboratory measurements. Since the dielectric constants of oil and ice are close to each other, it is difficult to detect an echo from the ice-oil layer in the presence of reflections from the air-ice and oil-water boundaries respectively. Without sophisticated signal processing or a better detection procedure, the VHF impulse radar is not useful for the detection of oil slicks under sea-ice.

There does seem to be a detectible effect on the detailed shape of the reflected pulse. It might be possible to develop correlation techniques to the point of detecting these changes.

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17. Résumé

Ce rapport résume une étude de faisabilité de détection de couches d'huiles sous les glaces de mer. Dans cette étude, les réflections de signaux VHF d'une couche d'huile sous les glace-de-mer ont été estimés et vérifiér par des mesures de laboratoire. Etant donné que les constants diélectriques d'huile et de glace sont proches, il est difficile de détecter un écho de la couche glace-huile dans la présence de réflections causées par les couches air-glace et huile-eau respectivement. Sans utilisation de traitement des donnés sophistiqués ou encore un système de détection amélioré, le radar à impulsion VHF ne serait pas utile à la detection de couches d'huiles sous les glaces de mer.

Toutefois, il semble y avoir un léger changement détectable dans la forme de l'impulsion réfléchie. Il pourrait être possible de developper des techniques de corrélation pour déceler ces changements.

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1. INTRODUCTION

With growing activities associated with arctic exploration, there is a growing threat of pollution from oil spills. Such pollution may be the result of blowout, pipeline breaks or oil spills from tankers. It often involves a significant amount of oil trapped and hidden under a layer of ice over the ocean surface. For an efficient pollution cleanup operation, it is useful to have a remote radar sensor that locates and tracks the oil spills.

At the request of the Transportation Development Centre, Transport Canada, MPB Technologies Inc. has conducted a short laboratory experiment in order to assess the feasibility of radio frequency techniques for oil detection. The purpose of this report is to present the experimental results. As a theoretical estimate given in Appendix 1 suggests, the radar echo due to the oil spill under an ocean ice layer would be relatively small and difficult to detect. This has been verified by the laboratory measurements.

There are many approaches for the remote sensing of oil slicks on the ocean surface with open water or sea-ice surface [1]-[8]. They include the fluorosensors, the microwave imaging radiometer, the scatterometer and the synthetic aperture radar (SAR). Yet none of them is suitable for detecting oil slicks under a thick layer of sea-ice (e.g thicker than 1 metre). The main difficulty lies in the strong absorption of electromagnetic radiation by sea-ice at frequencies above the VHF range. As it will be seen later, electromagnetic waves at VHF frequencies can penetrate into sea-ice.

It is, therefore, important to study the potential capability of VHF waves for under sea-ice probing of trapped oil. To assess the feasibility of a VHF sensor for this purpose, it is necessary to study at VHF the effects of oils on wave reflections at the ice-oil and oil-water interfaces.

In the experiment performed at MPB Technologies Inc., the antenna is replaced by a specially prepared two-wire transmission line. The line is placed in a salt water ice column prepared in a specially designed cold room facility. Oil is injected under the ice column and radio echoes are recorded for each oil thickness.

1.1 Sea-Ice Characteristics

Multi-year ice is relatively transparent to radio frequency waves. First year ice is usually highly attenuating at radio frequencies. Vant et al. [9] did a series of measurements in the laboratory on several types of natural sea-ice over the frequency range from 100 MHz to 40 GHz, (Fig. 1). The dielectric constant was found to range from 4 to 6 for the first year ice, and from 3.2 to 3.8 for the multi-year ice. It did not appear to be strongly frequency dependent. However, the attenuation by sea-ice was found to increase rapidly, with the frequency varying from 6 dB/m at 100 MHz to as much as 125 dB/m at 7.5 GHz for first year ice (Fig. 2). Values for multi-year ice appeared to be generally lower. The high frequency absorption of radio waves by sea-ice is, therefore, a major restriction to successful radar sounding of sea-ice and oil detection under first year ice, [10]. Typically, the skin depth for sea-ice with a salinity of 2‰ has been found to be in

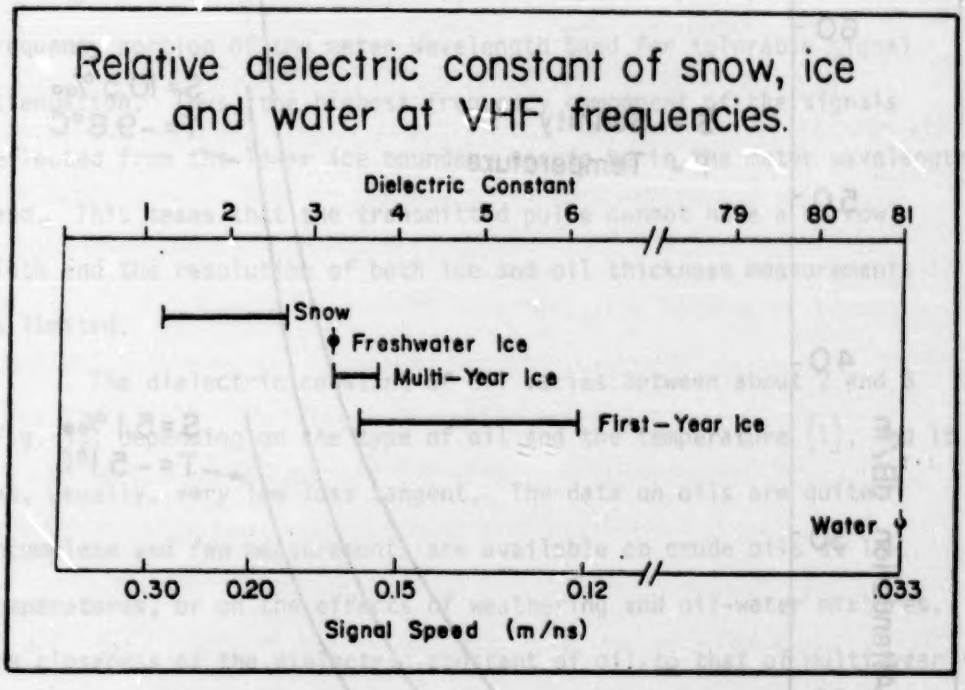

Figure 1: Sketch of dielectric constant of various types of sea ice and its constituents, pure ice and water. The dielectric constant controls the speed of a radar signal through the ice as indicated, and is not highly frequency-dependent from 1 MHz to 10 GHz.

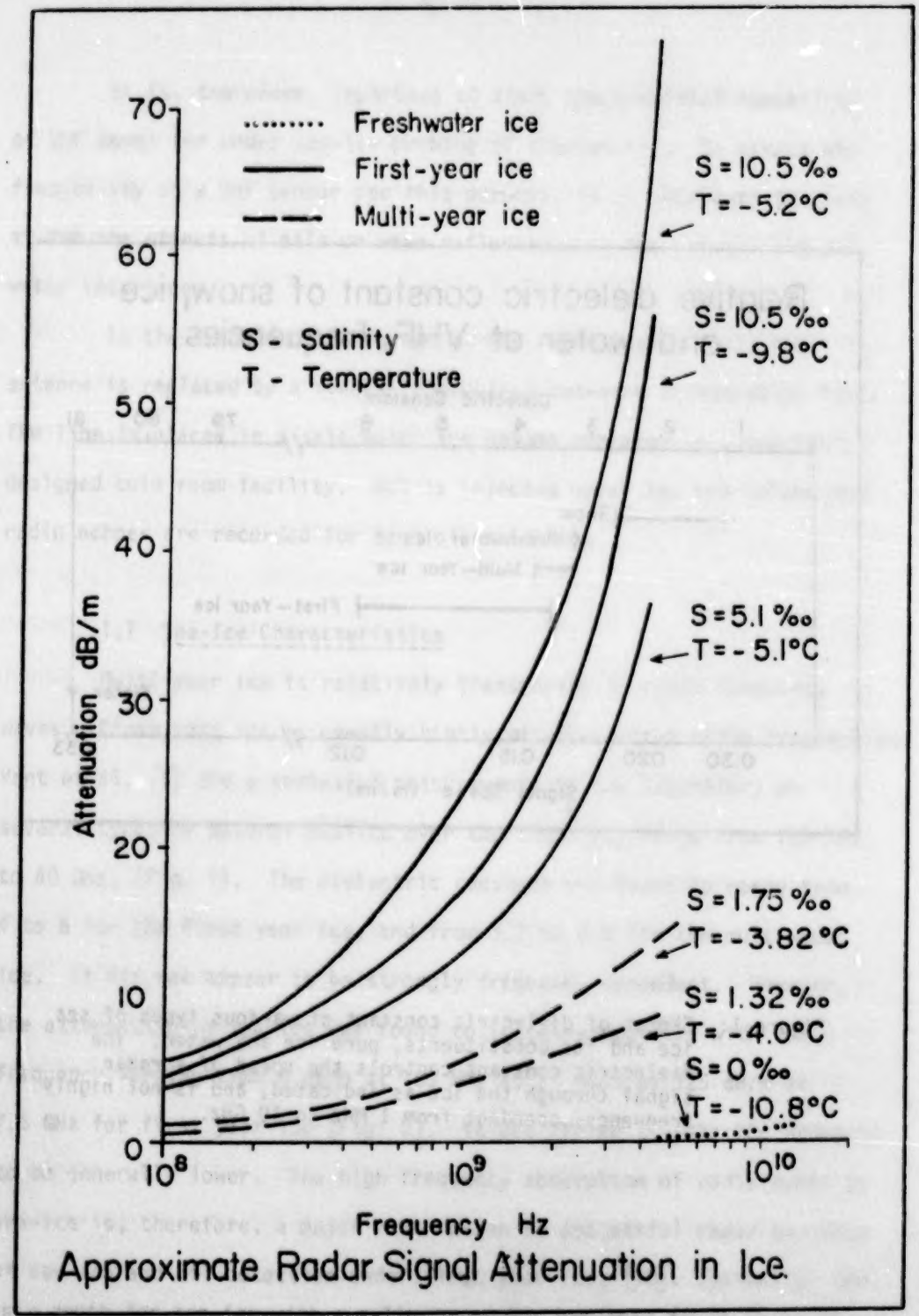

Figure 2: Sketch of the attenuation as a function of frequency for various types of ice. Note the rapid increase in attenuation at higher frequency and for higher salinity and/or temperature.

the order of one wave length at -10°C and decreases with increasing temperature and salinity [11]. This severely limits the use of higher frequency waves such as microwaves. In radar probing of sea-ice whose salinity is of the order of 5-12‰, it is necessary to utilize the low frequency portion of the meter wavelength band for tolerable signal attenuation. Thus, the highest frequency component of the signals reflected from the lower ice boundary has to be in the meter wavelength band. This means that the transmitted pulse cannot have a narrow width and the resolution of both ice and oil thickness measurements is limited.

The dielectric constant of oil varies between about 2 and 3 (Fig. 1), depending on the type of oil and the temperature [1], and it has, usually, very low loss tangent. The data on oils are quite incomplete and few measurements are available on crude oils at low temperatures, or on the effects of weathering and oil-water mixtures. The closeness of the dielectric constant of oil to that of multi-year ice, or even in some cases to that of first year ice, will reduce any possible reflection from ice-oil boundary. This can be seen from the relation for reflection coefficient Γ,

$$\Gamma = \frac{\sqrt{\varepsilon_{oil}} - \sqrt{\varepsilon_{ice}}}{\sqrt{\varepsilon_{oil}} + \sqrt{\varepsilon_{ice}}} \qquad (1)$$

where ε_{oil} and ε_{ice} are dielectric constants of oil and ice respectively. When $\varepsilon_{oil} \simeq \varepsilon_{ice}$ then the numerator of the above relation becomes negligible and hardly any reflected signal can be observed.

The following gives the experimental setup as well as the results of oil thickness measurements.

2. LABORATORY EXPERIMENT WITH RADAR ANTENNA REPLACED BY TRANSMISSION LINE

The transmission line technique of studying "radar echoes" serves several purposes. It provides a means of studying the propagation characteristics of radar signals through ice, the reflection characteristics of the ice and the oil boundaries, and the dispersive effects of the electronic components and the propagation media on the radar pulse shape.

In the transmission line technique, the antenna is first replaced by a specially prepared two-wire transmission line in free space [12]. Artificial discontinuities are introduced to study the echo waveforms and the effects of transients. The transmission line is then immersed in a salt water ice column. Results of these two experiments allow one to study independently the dispersive effects of the electronics, the transmission line, the ice column and the oil layer on the echo waveforms, and the ultimate thickness resolution of the radar system.

Since the radar signals are guided and confined in the neighbourhood of the transmission line, the test medium needs only occupy a small volume around the line. The lateral boundaries of the medium or nearby objects can be neglected if their distances from the transmission line are large compared with the lateral dimensions of the line. Thus the experiment can be performed in the laboratory without an enormous anechoic chamber or a quiet test range. The ice column can have a reasonably small diameter

and can be grown in an upright freezer. The ice "thickness" (i.e. the column height) can be varied quickly in minutes or hours rather than days or weeks as in most ice growing facilities.

2.1 The Experiment

The experimental arrangement to test the radar with its antenna replaced by a transmission line in free space is shown in Fig. 3. Signals from the radar transmitter are fed to a specially prepared 300Ω two-wire line test section through a transformer and a delay line. The transformer is necessary to provide a smooth transition between the delay line which is a long piece of 50Ω coaxial line and the 300Ω two-wire line test section.

Since the test section of the transmission line would be immersed in the ice column in a later experiment, its design and construction required some consideration. The transmission line test section should propagate transverse waves, have an open structure with suitable lateral dimensions, a simple configuration for ease of construction and ease of adding matched terminations or discontinuities on the line.

The open structure allows salt water or ice to occupy the regions where the electromagnetic waves propagate. Thus the salt water or ice act as a dielectric medium for the transmission line and will have dominant effects on the propagation waves. With small lateral dimensions, the transmission line confines waves in its neighbourhood and the cylindrical wall of the ice column can be

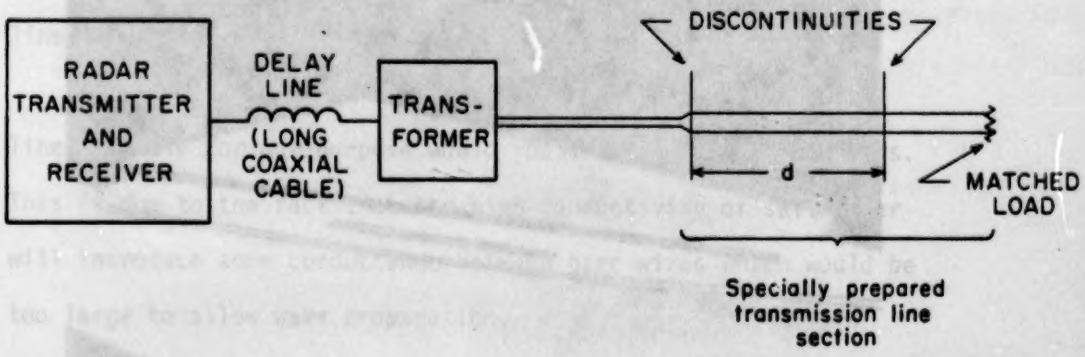

Figure 3a Sketch showing experimental arrangement to test radar using transmission line in free space

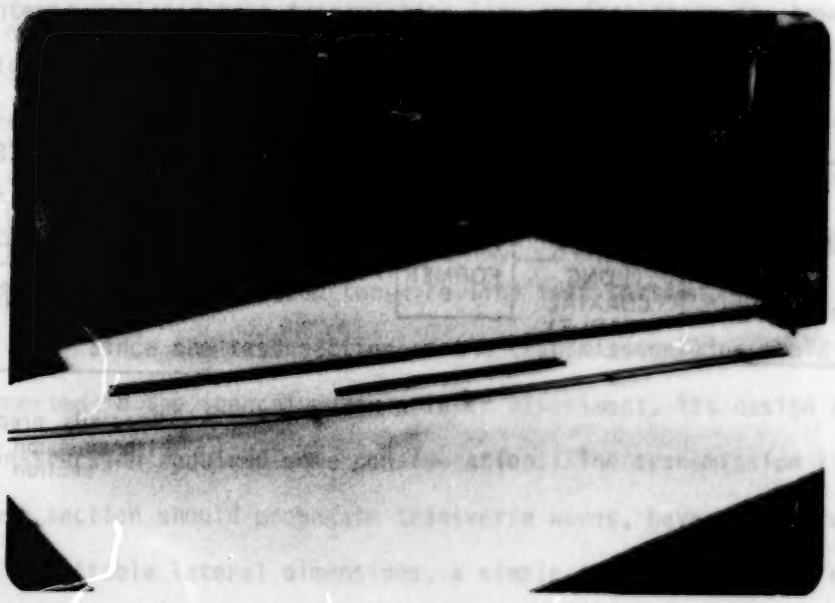

Fig. 3b. Picture of specially prepared transmission line test section. Black insulated two-wire line is shown in middle. Uninsulated line is near bottom of picture.

neglected. However, an estimate has to be made to ensure that this condition is satisfied, otherwise we will not have TEM wave with $v = \frac{c}{\sqrt{\varepsilon}}$ where v is the speed through the material, c the speed of light and ε the dielectric constant of material. In this case, the whole ice column may act as a waveguide and its cylindrical boundary is no longer negligible. For convenience in experimental measurements, the transmission line should enable one to add or remove easily artificial discontinuities along the line.

It should be mentioned here that the prepared two-wire line suitable for our purpose would require insulated conductors. This is due to the fact that the high conductivity of salt water will introduce some conductance between bare wires which would be too large to allow wave propagation.

The insulated two-wire line in our measurement used two RG58/U cables with the outer conductors of the parallel cables forming the two-wire line.

2.2 Transmission in Ice Column

The experimental arrangement for measurements with the transmission line immersed in a salt-water ice column was as shown in Fig. 4. It was designed to simulate the transmission of a radar signal from the signal generator through a transmitting antenna, the space between the antenna and the target, the ice layer, and the return path to the radar receiver. Thus the bandwidth limitation effects of the antenna, the signal attenuation,

and the time delay due to the radar range were simulated with the help of a transformer and a relatively glossy coaxial cable. Radar signals were fed through the salt water ice column with an insulated two-wire line described in the last section. The two-wire line ended in the salt water at the bottom of the ice column and was terminated with a resistance corresponding to the characteristic impedance of the line in salt water.

In the following section, we will describe the experimental arrangement in greater detail. Since the most important components of the experimental setup were the cold room facility and the ice column facility, they will be discussed in sections 2.2.1 and 2.2.2 respectively. The experimental procedure will be described in section 2.2.3, with the measurements presented in section 2.2.4.

2.2.1 Cold Room Facility (Fig. 4a, b and c)

The cold room is a relatively inexpensive facility for studying wave reflections from oil trapped under ice. It enables one to study the wave reflections at ice-air, ice-oil and oil-water boundaries respectively. It consists of a custom-made upright freezer with suitable dimensions to house an ice-column facility. Its inner dimensions are 51 cm wide, 61 cm deep and 198 cm high. It could maintain a thermostatically controlled temperature down to -50^{o}C and could prepare an ice column up to 1.9 metres high.

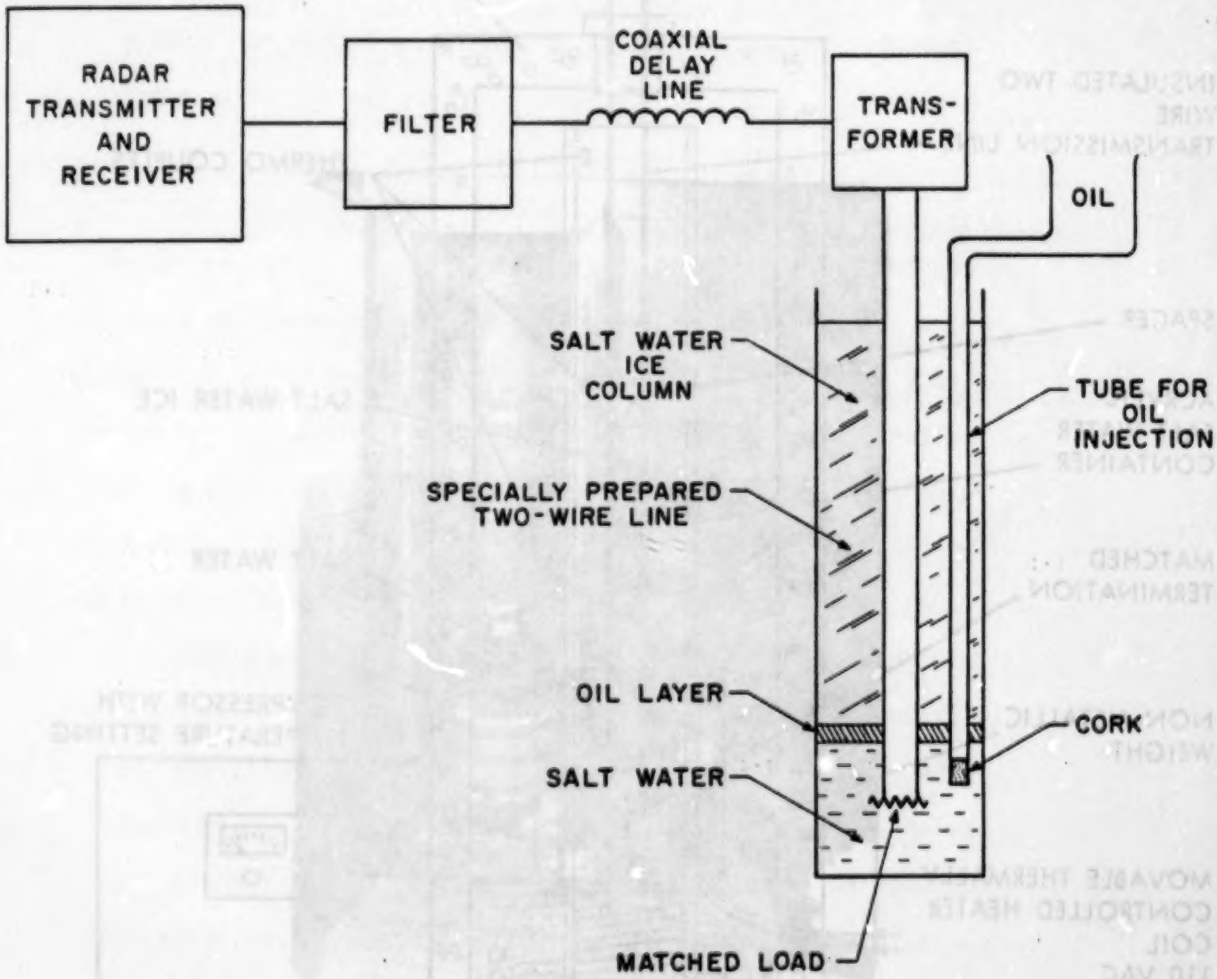

Fig. 4a. Sketch of experimental arrangement to test sensor with transmission line in ice. Filter and delay line simulate loss, range and antenna response in actual operational environments. Transformer matches delay line to specially prepared two-wire line. Ice column is prepared and housed in freezer. Its height can be varied by heating water at bottom.

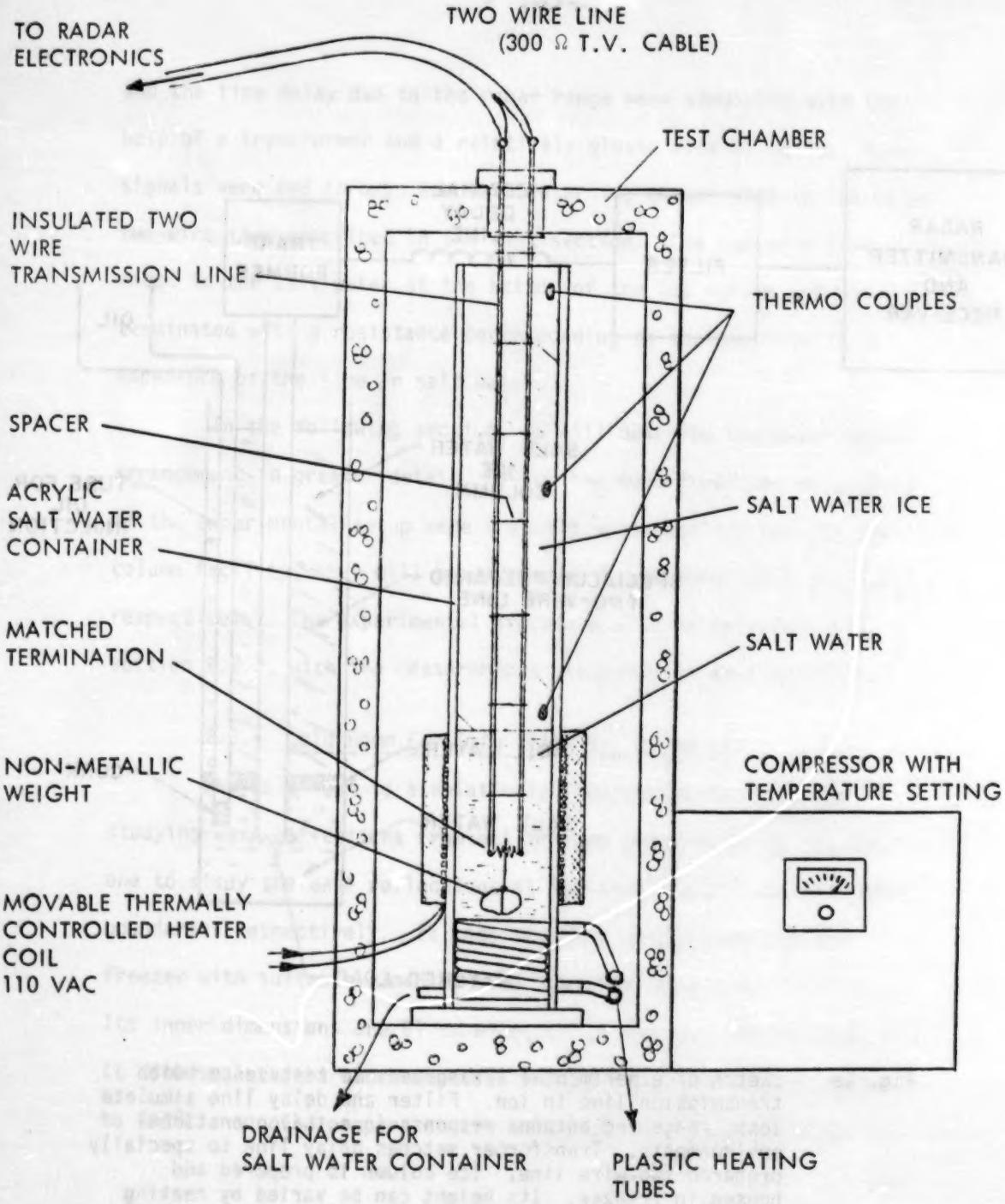

Fig. 4b. Sketch of Cold Room Facility

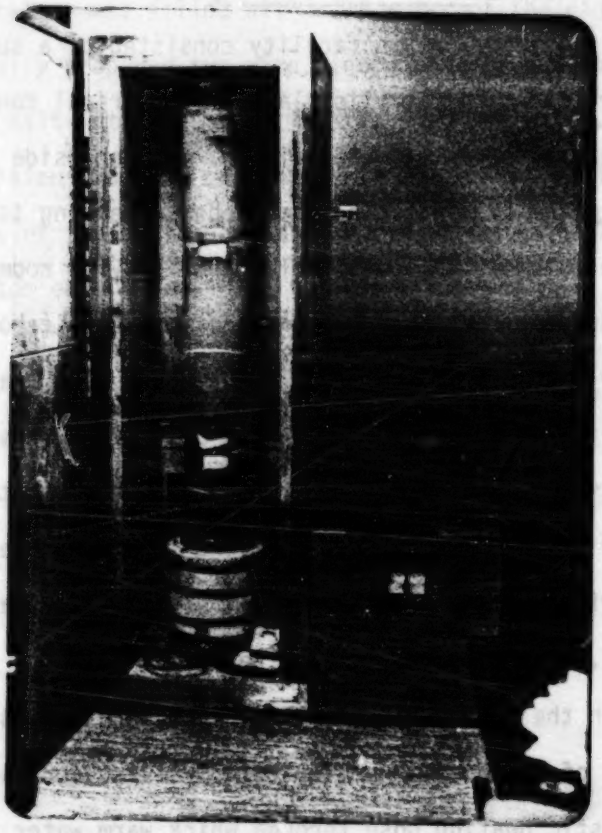

Fig. 4c: Picture showing interior of cold room facility

On top of the freezer was a 12 cm diameter hole to be used as a "feed-through" for the transmission line. Feed-through holes were also available near the bottom for feeding electrical cables or water hoses required for the measurements.

2.2.2 Ice Column Facility

The ice column facility consisted of a specially constructed clear acrylic plastic cylindrical container 180 cm high and 20 cm in diameter (i.d.). Near one side of the container was a piece of synthetic foam rubber extending to the full height of the column. This was included to provide room for ice expansion during freezing. A long and rigid hose (about 1.5 m) was placed right in front of the foam rubber as a means to inject oil under ice column. The bottom end of the hose was slightly below the desired lower ice boundary and was sealed with a cork. The latter prevents water from entering into the hose which would otherwise be filled with ice in the process of making the ice column. The upper end of the hose was taken out of the freezer through the hole on top of the freezer and it was connected to a tank of crude oil. At the bottom of the container was a coil of plastic heating hose through whick warm water could flow to maintain some water underneath the ice column. The height of the water level and hence the ice column could be changed by varying the rate of heating. Additional heating was provided by a thermally controlled electric heating coil wrapped around the container. The electric heater could be moved up and down.

Thus a particular section of the ice column could be heated or melted to create a multilayered column or simply to speed up heating at the bottom.

To prepare an ice column for echo sounding measurements, the container was filled with salt water of the right salinity. A specially prepared two-wire line with a proper matched termination in salt-water was then lowered into the water. The transmission line was maintained in a vertical position along the axis of the container by attaching a non-metallic weight at its bottom end.

3. EXPERIMENTAL RESULTS

For the laboratory experiment, two sets of measurements have been taken with the radar transmitter operating in the impulse radar (IMR) mode and the synthetic pulse (SPR) mode respectively. The former transmits simple repetitive video pulses whereas the latter transmits series of video pulses synthesized from five harmonically related signals. Thus respective results will be summarized in the following sections.

3.1 Measurements Using Impulse Radar Mode

An ice column was prepared by keeping the cold room at $-30^{o}C$. The water near the bottom of the plastic container was kept from freezing by the thermally controlled electric heater. It took about two days to prepare the salt water ice column. To investigate the effect of the cable and impedance transformer on a transmitted pulse, a short circuit was placed right before the transformer and the return signal was recorded. Then the short was moved to a location immediately after the transformer and again the reflected signal was recorded. Figure 5 shows the results of this experiment with a 5 nsec pulse. It is clear that the transformer causes the trailing edge of the pulse to cross zero level with a slow recovery time. The amplitude of the pulse is also reduced by more than 20% in the two-way passing through the transformer due to insertion loss. The reflections of the radar signals from the top and bottom ice surfaces were observed at the oscilloscope.

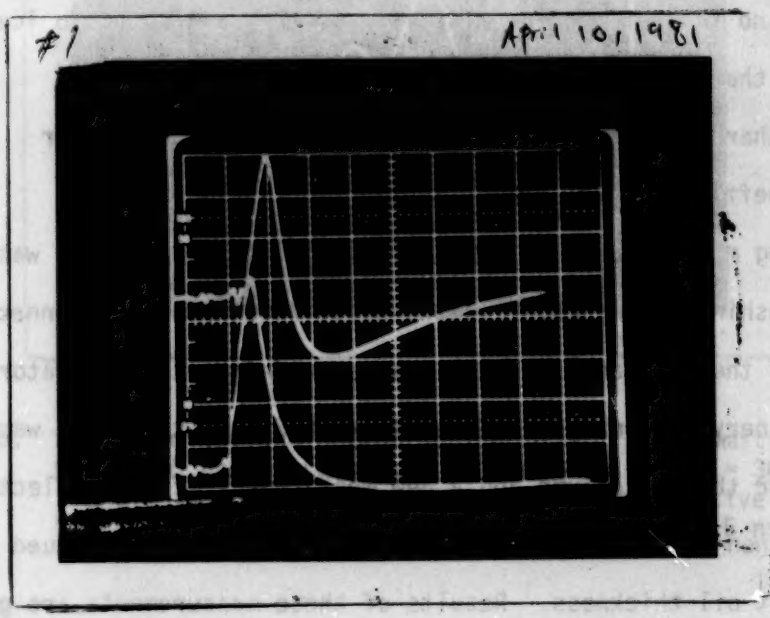

Fig. 5. Effect of impedance transformer on transmitted pulse. Short circuit placed (a) after transformer and (b) before transformer.

The results are shown in Figure 6. It is to be noted that the top return is smaller in amplitude than the bottom return. This is due to the fact that relatively cold ice (at -30°C) has a small attenuating effect and the ratio of permittivity of the salt water to ice is much greater than that of the ice to free space. Referring to equation 1, therefore, the ice-water boundary has a much larger reflection coefficient.

During measurements the cork in the oil injection hose was removed by pushing a long rod into the hose, which was then connected to the tap of the oil tank. The oil was provided by the laboratory of Shell Refinery in Montreal. Some oil with 2.5 cm thickness was injected under the ice column and a new measurement of the reflected signals was then taken (Figure 7). The measurement was continued with different oil thickness. Results of these measurements are given in Figures 8 - 11. It is seen that there is a progressive time delay of the ice bottom reflection. In addition, there is a reduction of signal strength for the ice-bottom reflection, which also increases with the increase of oil thickness. This change of signal strength could be a sign of a change in electrical properties at the bottom of ice, that is, a transition from ice to oil layer.

3.2 Measurements Using Synthetic Pulse Radar Mode

A synthetic pulse radar (SPR) transmits a signal composed of a number of harmonically related frequencies. When the relative amplitude and phase of each frequency component is suitably selected,

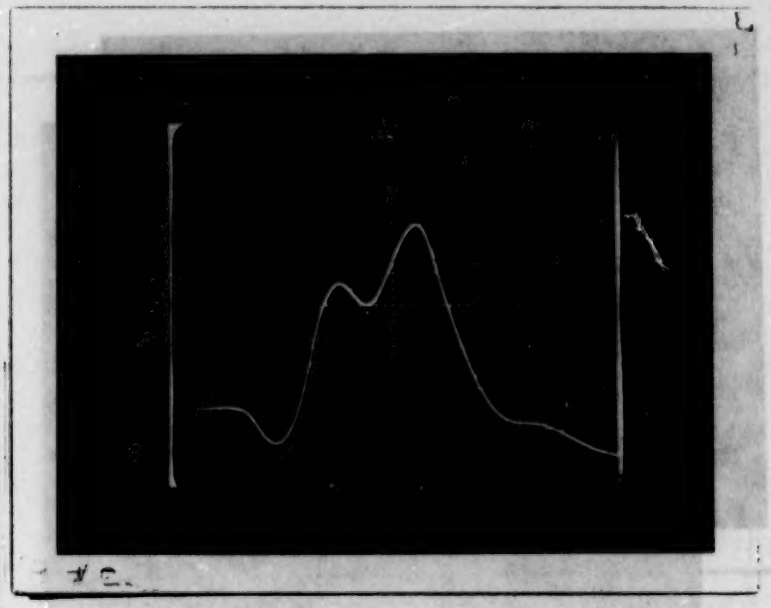

Fig. 6. Echo from top and bottom of ice column. Transmitted pulse width = 5 nsec, ice height = 84 cm, ice temp. = 30°C. t and b indicate top and bottom echoes respectively. Vertical scale arbitrary. Horizontal scale = 5 nsec/div.

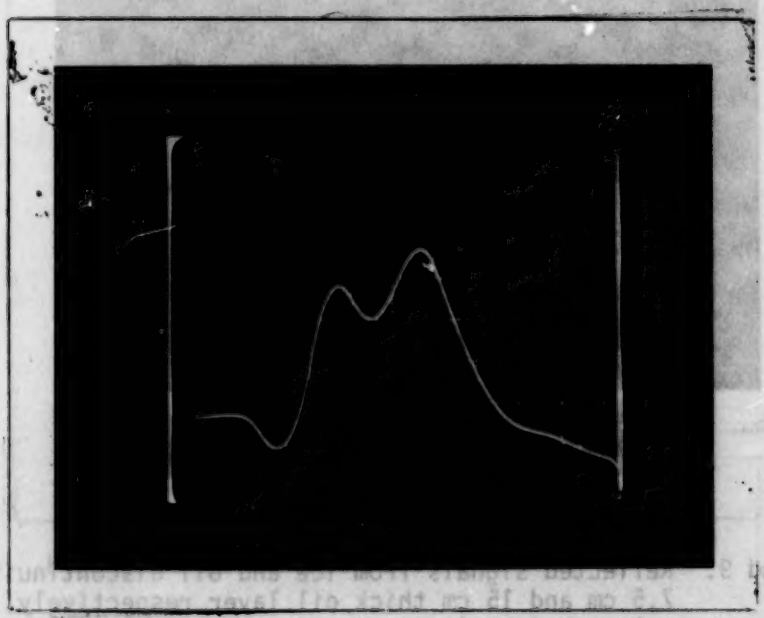

Fig. 7. Reflected signals from 84 cm ice column with 2.5 cm oil layer underneath. Ice temp. = -30°C. Vertical scale arbitrary. Horizontal scale = 5 nsec/div.

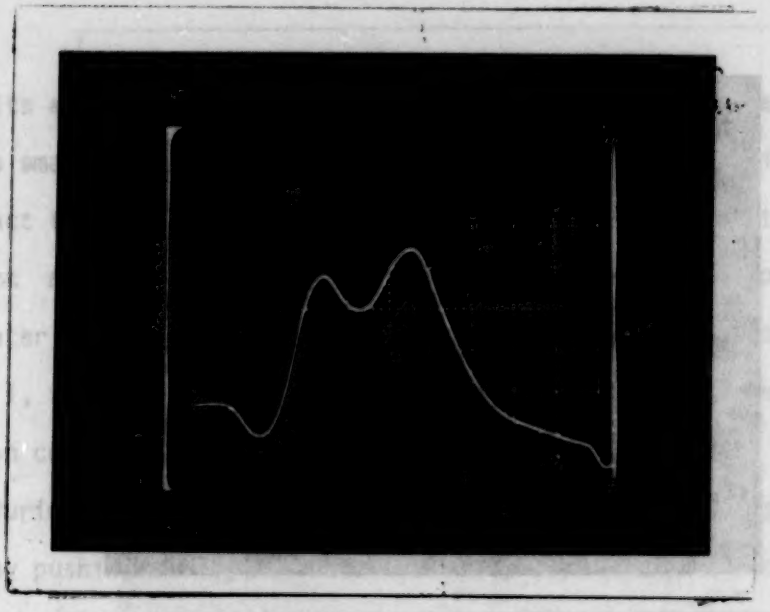

Fig. 8. 7.5 cm thick oil layer

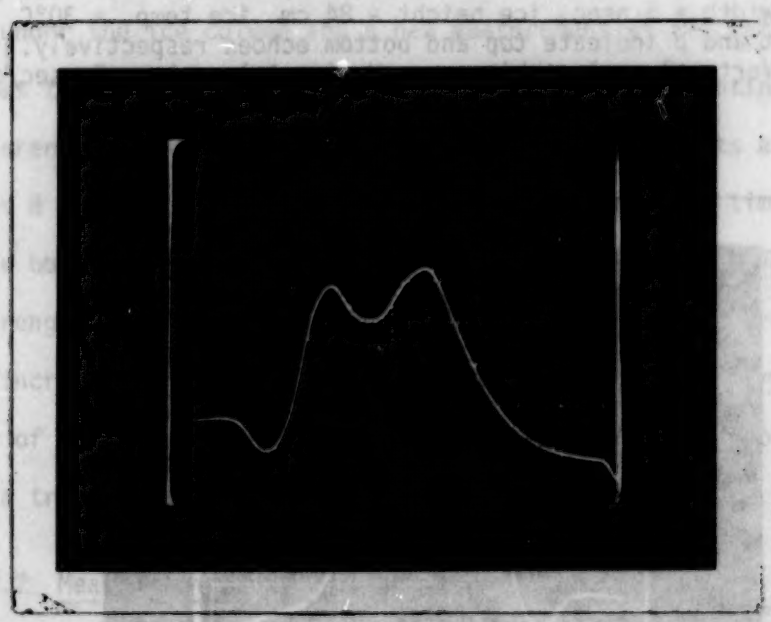

Fig. 9. 15 cm thick oil layer

Fig. 8 and 9. Reflected signals from ice and oil discontinuities for 7.5 cm and 15 cm thick oil layer respectively. Ice column height is 84 cm. Temperature = -30°C.

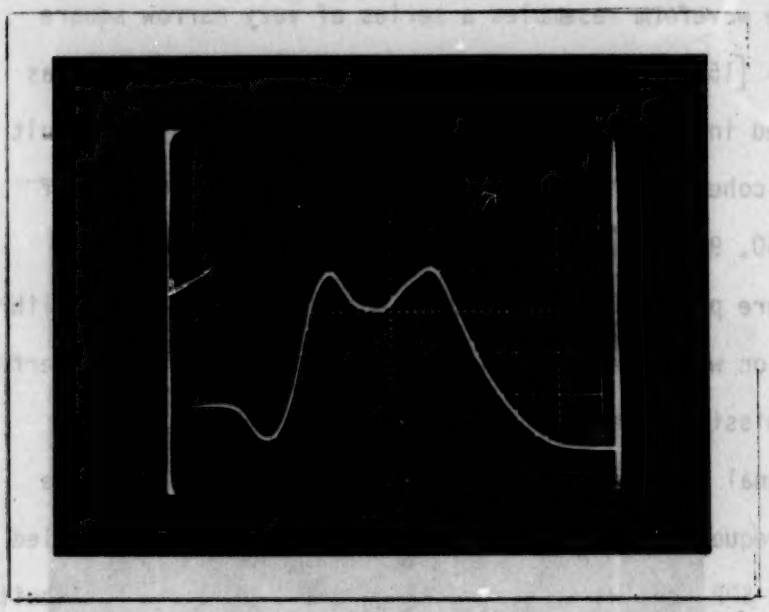

Fig. 10. 20 cm thick oil layer

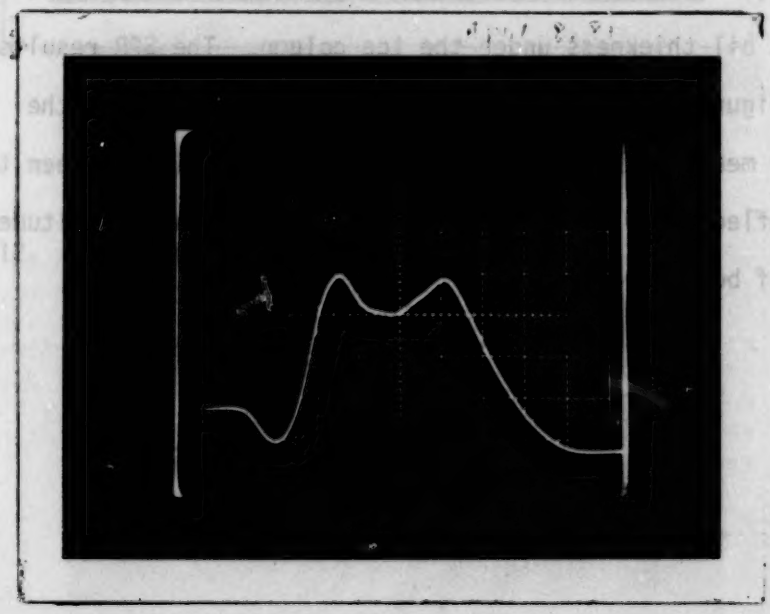

Fig. 11. 25 cm thick oil layer

Fig. 10 and 11. Echoes from ice-air, ice-oil and oil-water boundaries respectively for 20 cm and 25 cm thick oil layers respectively.

the composite waveform resembles a series of very narrow square pulses [13] - [15]. Figure 12 shows the output of SPR which has been developed in MPB Technologies Inc. The signal is the result of combining coherently 5 signals with fundamental frequency of 30 MHz (30, 60, 90, 120 and 150 MHz) with right amplitudes and phases. Before proceeding with the experiment, the SPR was calibrated. The calibration was done by placing a short circuit at the interface of the transmission line and the ice column and observing the reflected signal on the scope. The gains and the phases of the individual frequency components in transmitted signal were varied until a clean SPR echo was observed, Figure 13. The short circuit was removed and the reflection signal from the bottom and top of the ice recorded (no oil), Figure 13. Then the experiment was repeated for different oil thickness under the ice column. The SPR results, as given in Figure 14 - 16, were found to be consistent with the impulse radar measurements, i.e., increase in time delay between top and bottom reflection with increase in oil thickness and amplitude attenuation of bottom reflection.

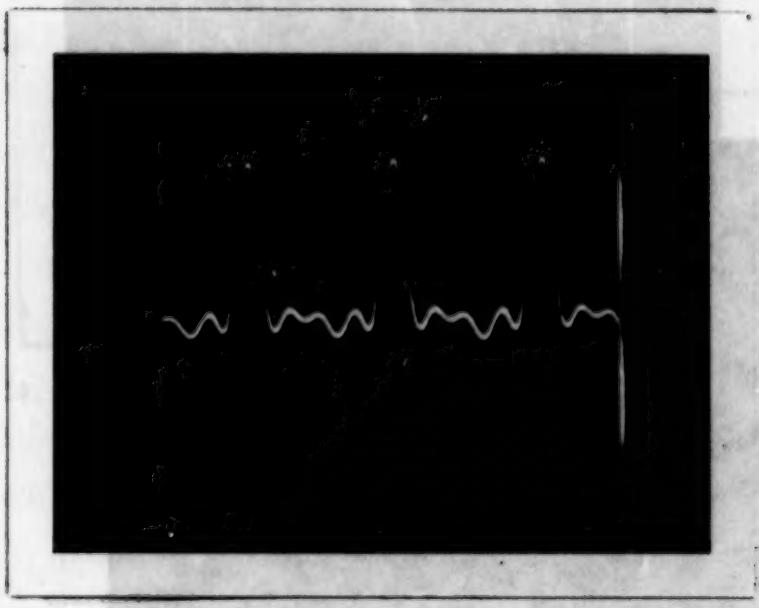

Fig. 12. Transmitted synthetic pulse.

Vertical scale = arbitrary
Horizontal scale = 10 nsec/div.

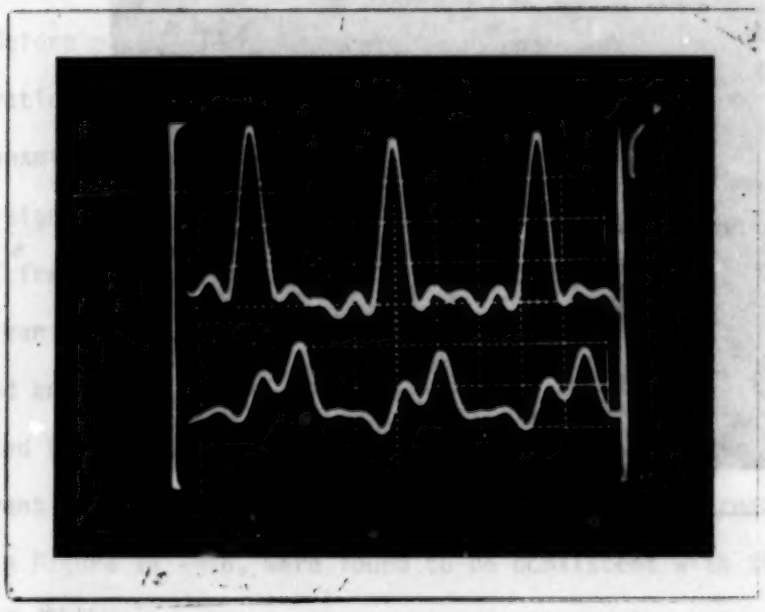

Fig. 13. SPR echoes from (A) a short circuit and (B) a 78 cm ice column respectively. Horizontal scale is 10 nsec/div. Vertical scale is arbitrary. In (A), reflection from a short circuit placed after the impedance transformer gives a series of single pulses (peaks). (B) shows a series of double peaks corresponding to echoes from the air-ice boundary (the earlier peaks) and the ice-water boundary (the later peaks) respectively.

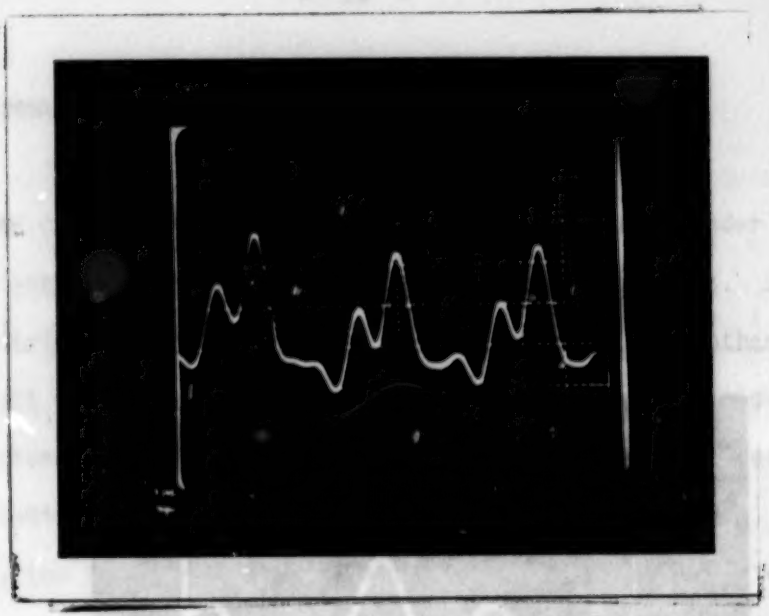

Fig. 14. Echo from 78 cm ice column with 4 cm oil underneath. Vertical scale = arbitrary. Horizontal scale = 10 nsec/div.

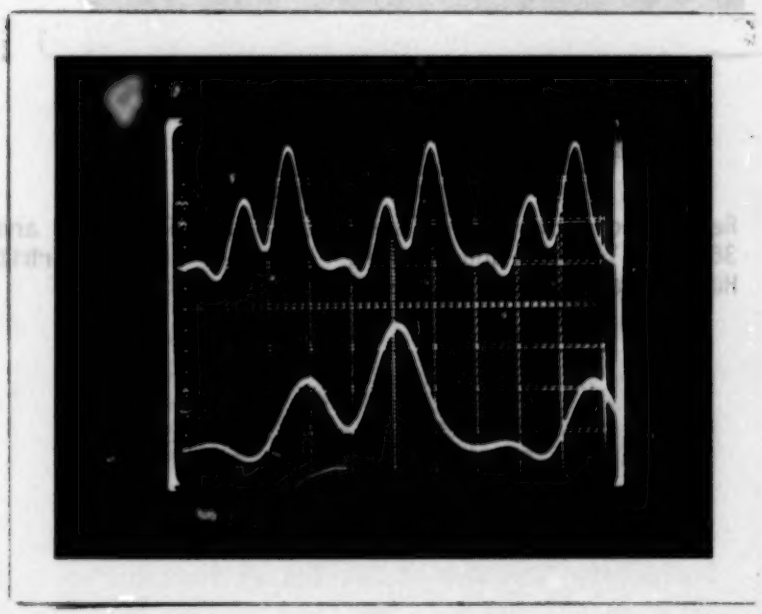

Fig. 15. Echo from 75 cm ice column with 20 cm oil layer. Vertical scale = arbitrary. Horizontal scale = 10 nsec/div. for upper trace; 5 nsec/div. for lower trace.

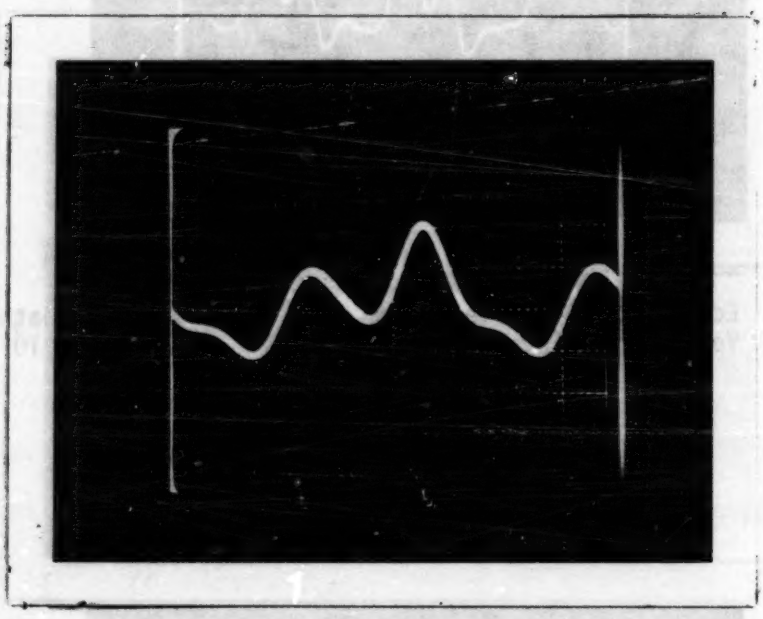

Fig. 16. Reflected synthetic pulse from 75 cm ice column and 36 cm oil layer underneath. Vertical scale = arbitrary. Horizontal scale = 5 nsec/div.

4. SUMMARY AND CONCLUSION

The reflections of VHF signals from an oil layer under sea-ice have been estimated and verified by laboratory measurements. Since the dielectric constants of oil and ice are close to each other, it is difficult to detect an echo from the ice-oil layer in the presence of reflections from the air-ice and oil-water boundaries respectively. Without sophisticated signal processing or a better detection procedure, the VHF impulse radar is not useful for the detection of oil slicks under sea-ice.

There does seem to be a detectible effect on the detailed shape of the reflected pulse. It might be possible to develop correlation techniques to the point of detecting these changes.

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APPENDIX 1

ESTIMATES OF RELATIVE AMPLITUDES OF RADAR ECHOES FROM AN OIL LAYER UNDER SEA ICE

Using typical values of the dielectric constraints of ice, oil and water, it is easy to estimate the reflections of a typical VHF signal pulse from a layer of sea ice with trapped oil sandwiched between the ice and water (see Fig. A1).

The reflection coefficient R_{ij} back into the ith layer at the interface between the i^{th} and j^{th} layers is given by

$$R_{ij} = (\varepsilon_i^{1/2} - \varepsilon_j^{1/2})/(\varepsilon_i^{1/2} + \varepsilon_j^{1/2})$$

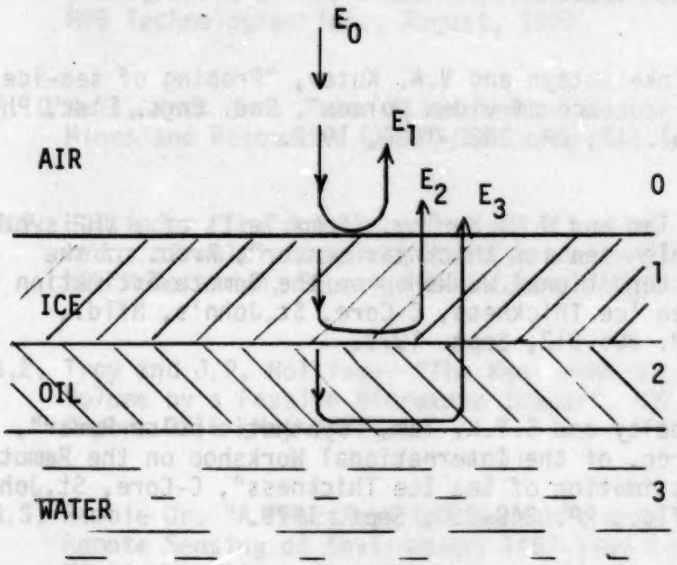

Fig. A1. Sketch showing reflections of VHF signals from air, ice, oil and water boundaries. E_0, E_1, E_2, E_3 are the incident and reflected signals back into free space as a result of reflections from the respective boundaries as indicated.

where ε_i is the relative dielectric constant of the ith layer with respect to free space.

The attenuation through the ith layer of thickness l_i is given by $e^{-(Im\varepsilon_i^{1/2})k_0\ell_i} = e^{-\alpha_i\ell_i}$ where k_i is the free space wave-number and α_i the attenuation per unit length of the VHF signal in the ith layer. $Im\varepsilon_i^{1/2}$ is the imaginary part of the complex quantity $\varepsilon_i^{1/2}$.

The incident and reflected signals E_0, E_1, E_2, E_3 are respectively given by

$$E_0$$

$$E_1 = E_0R_{01},$$

$$E_2 = E_0(1 - R_{01}^2)R_{12} \exp(-2k_o\varepsilon_1^{1/2}\ell),$$

$$E_3 = E_0(1 - R_{01}^2)(1 - R_{12}^2)R_{23} \exp\left[-2k_0(\varepsilon_1^{1/2}\ell_1 + \varepsilon_2^{1/2}\ell_2)\right].$$

For estimates of E_1, E_2, and E_3 we choose typical values of the relative dielectric constants for air, ice, oil and water as follows:

$\varepsilon_0 = 1$ for air

$\varepsilon_1 = 4 + 0.1j$ for sea ice (depending on ice salinity)

$\varepsilon_2 = 2.25$ for crude oil

$\varepsilon_3 \approx 80 + 80j$

These and the previous formulas for R_{ij} and E_i give

$$E_1 = -.3E_0$$

$$E_2 = 0.13E_0 \exp\left[-2k_0\ell\varepsilon_1^{1/2}\right]$$

$$E_3 = -0.63E_0 \exp\left[-2k_0(\ell_1\varepsilon_1^{1/2} + \ell_2\varepsilon_2^{1/2})\right]$$

The corresponding powers reflected are proportional to

$$|E_1|^2 \approx 0.1\ |E_0|^2,$$

$$|E_2|^2 \approx 0.017\ |E_0|^2 \exp\left[-\alpha_1\ell_1\right]$$

$$|E_3|^2 \approx 0.4\ |E_0|^2 \exp\left[-\alpha_1 \ell_1 - \alpha_2 \ell_2\right]$$

These simple estimates show that the signal E_2 reflected at the ice-oil interface is small compared with the other signals and is especially difficult to detect in the presence of E_3, the reflection at the oil-water interface.